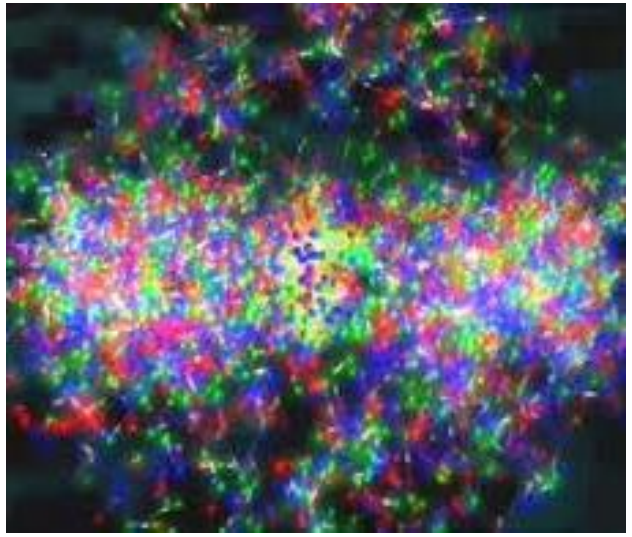
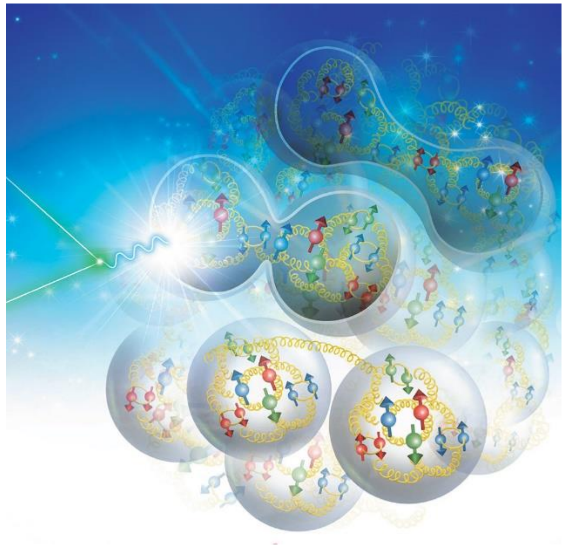
EF07 Heavy Ions: Highlights and Plans



Co-conveners:
Yen-Jie Lee (MIT), Swagato Mukherjee (BNL)

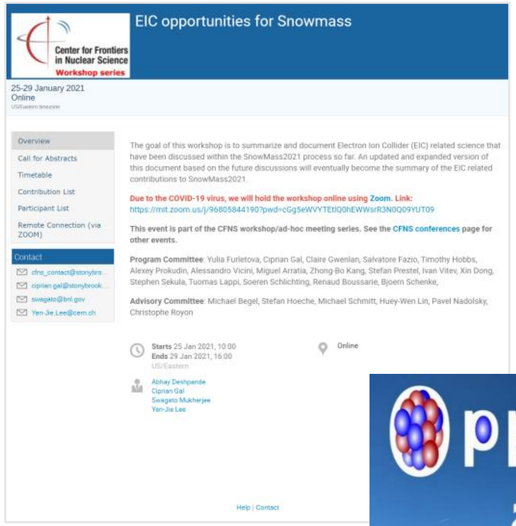


Energy Frontier Workshop - Restart

September 3, 2021

MIT group's work was supported by US DOE-NP

Workshops This Year



EIC Opportunities for Snowmass (25-29 January 2021)

https://indico.bnl.gov/event/9376/

Organizer: Abhay Deshpande, Ciprian Gal, Swagato Mukherjee, Yen-Jie Lee

Opp**O**rtunities at the LHC (4-10 February 2021)

https://indico.cern.ch/event/975877/

Organizer: Jasmine Therese Brewer, Aleksas Mazeliauskas, Wilke van der Schee

Heavy Ions and New Physics (20-21 May 2021)

https://indico.cern.ch/event/831940/

Organizer: Marco Drewes, David d'Enterria Andrea, Giammanco, Jan Hajer

EF07 Parallel Session

11:00 AM → 12:00 PM **Parallel Session G: EF07**

Conveners: Swagato Mukherjee (BNL) , Yen-Jie Lee (CERN) , Yen-Jie Lee (Massachusetts Institute of Technology)

Zoom Link - Meetin... | Parallel G recording

Heavy Ions

11:02 AM **Workshop Summary: Heavy Ion and New Physics** — 14m

Speaker: Jan Hajer (Université catholique de Louvain)

Workshop summary...

11:16 AM **Workshop Summary: Opportunities of OO and pO collisions at the LHC** — 14m

Speaker: Wilke van der Schee (CERN)

talk_snowmass.pdf

e^+e^-

11:30 AM **LEP jet studies and its implications to future EIC measurements** — 6m

Speaker: Yi Chen (MIT)

20210902_EEJetEIC...

EIC

11:36 AM **Heavy Flavor @ EIC** — 8m

Speakers: Ivan Vitev (Los Alamos National Laboratory) , Stephen Sekula (Southern Methodist University) , Xin Dong (Lawrence Berkeley National Laboratory)

Snowmass-EF07-He...

11:44 AM **Jets @ EIC** — 8m

Speakers: Prof. Miguel Arratia (University of California, Riverside & Thomas Jefferson National Laboratory) , Zhongbo Kang (UCLA)

Snowmass Jets EIC...

11:52 AM **Gluon saturation @ EIC** — 8m

Speaker: Bjoern Schenke (BNL)

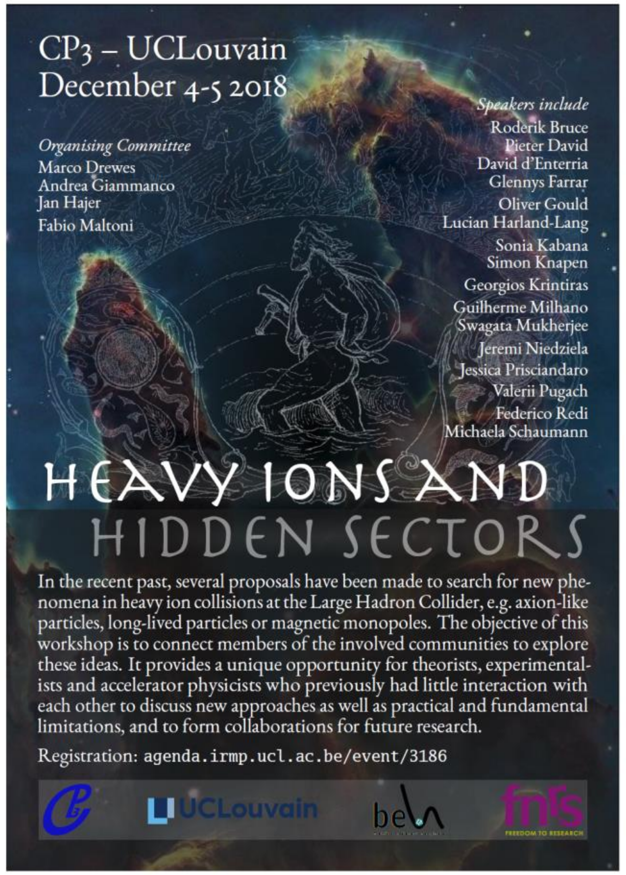
Schenke-Saturation....

6 speakers,
~20 participants

Heavy Ions and New Physics

- Second successful workshop on New Physics searches in heavy ion collisions
- Potential New Physics (more than presented in this talk)
  - Magnetic monopoles
  - Axion-like particles
  - Sexaquarks
  - Dark photons
  - Soft New Physics
  - Long-lived New Physics
- Connection to
  - Cosmic ray air showers
  - τ-lepton $g-2$
  - Gravitational waves

2018 workshop



First workshop resulted in contribution to 'European Strategy for Particle Physics' (ESPP)

New physics searches with heavy-ion collisions at the CERN Large Hadron Collider

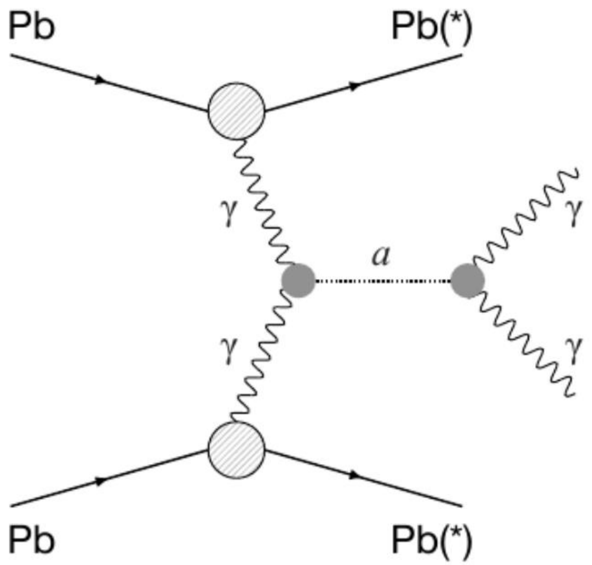
Roderik Bruce[1], David d'Enterria[2,18], Albert de Roeck[2], Marco Drewes[3], Glennys R Farrar[4], Andrea Giammanco[3], Oliver Gould[5], Jan Hajer[3], Lucian Harland-Lang[6], Jan Heisig[3], John M Jowett[1], Sonia Kabana[7,16], Georgios K Krintiras[3,17], Michael Korsmeier[8,9,10], Michele Lucente[3], Guilherme Milhano[11,12], Swagata Mukherjee[13], Jeremi Niedziela[2], Vitalii A Okorokov[14], Arttu Rajantie[15] and Michaela Schaumann[1]

J. Phys. G 47 (2020) 6, 060501
e-print: 1812.07688 [hep-ph]

Jan Hajer

HI and NP: ALP Search

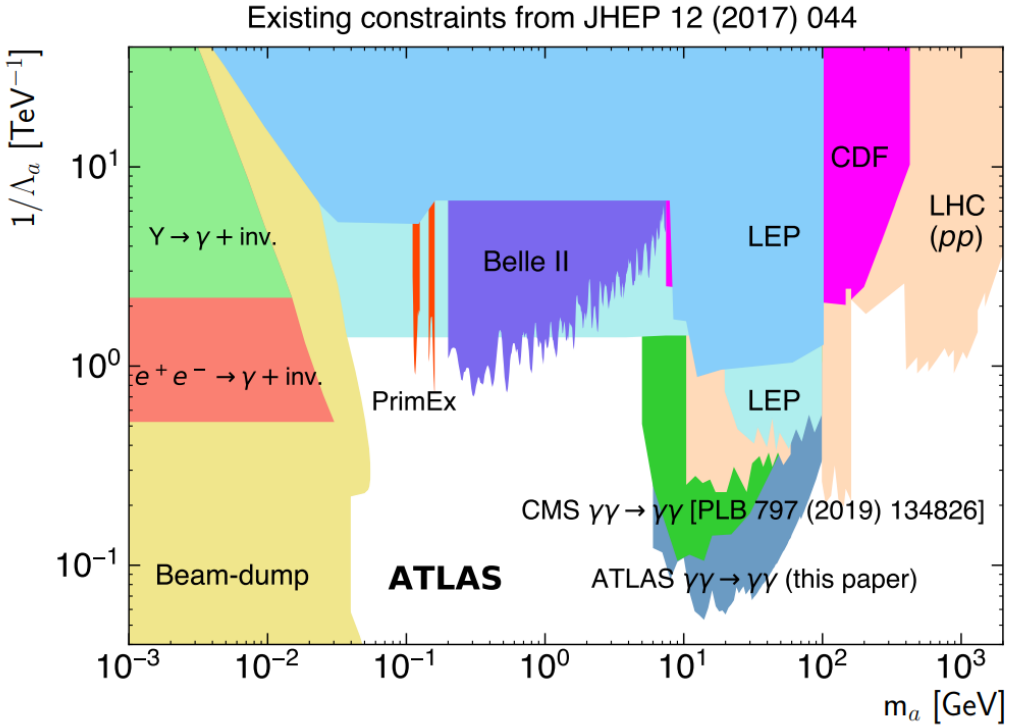
Ultra peripheral HI collisions



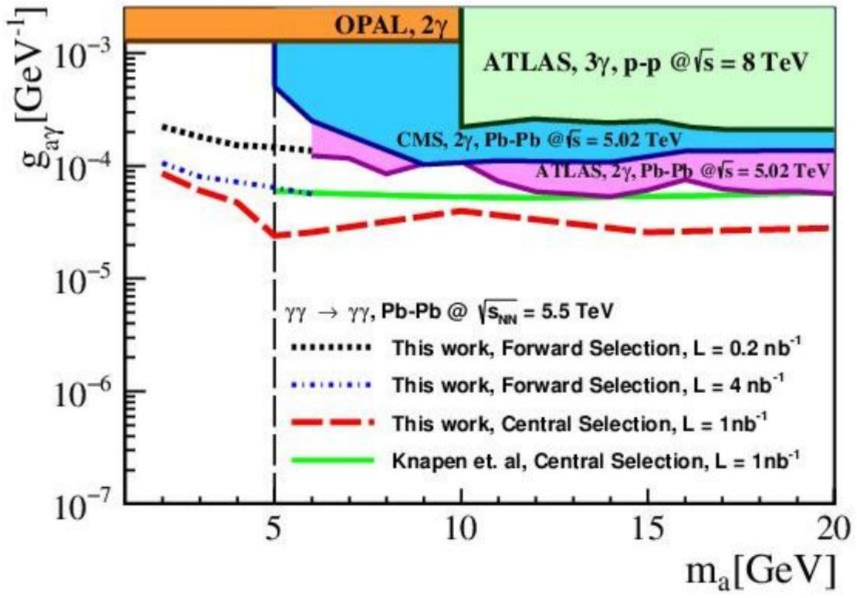
Magnetic field in 5.02 TeV PbPb

$|B| \simeq 4 \cdot 10^{16}\,\mathrm{T} \simeq 7\,\mathrm{GeV}^2$

Exclusion with 2.2 nb^{-1} 2021



PbPb



Projection with LHCb

Expected to surpass current limits

for masses below 5 GeV

Light ALPs also accessible @ ALICE

Potential New Physics search without competition by CMS or ATLAS

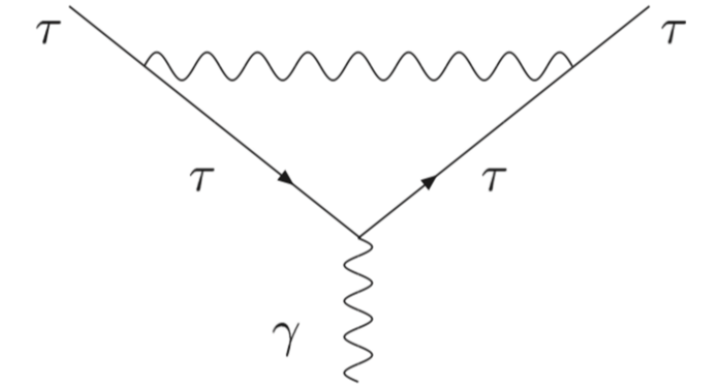
Jan Hajer

- ALP and Monopole searches: rely on the large EM field in heavy ion collisions.
- Performance with MoEDAL, LHCb, CMS, ATLAS and ALICE presented in this workshop

HI and NP: Tau g-2

anomalous magnetic moment

$a_\tau = (g_\tau - 2)/2$



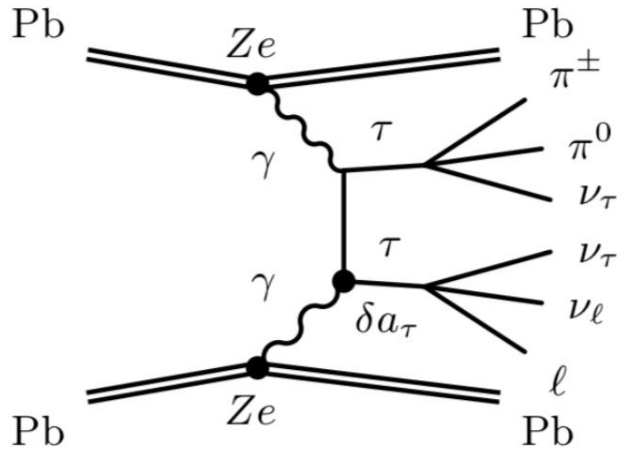
Constraint from DELPHI

$-0.052 < a_\tau < 0.013$

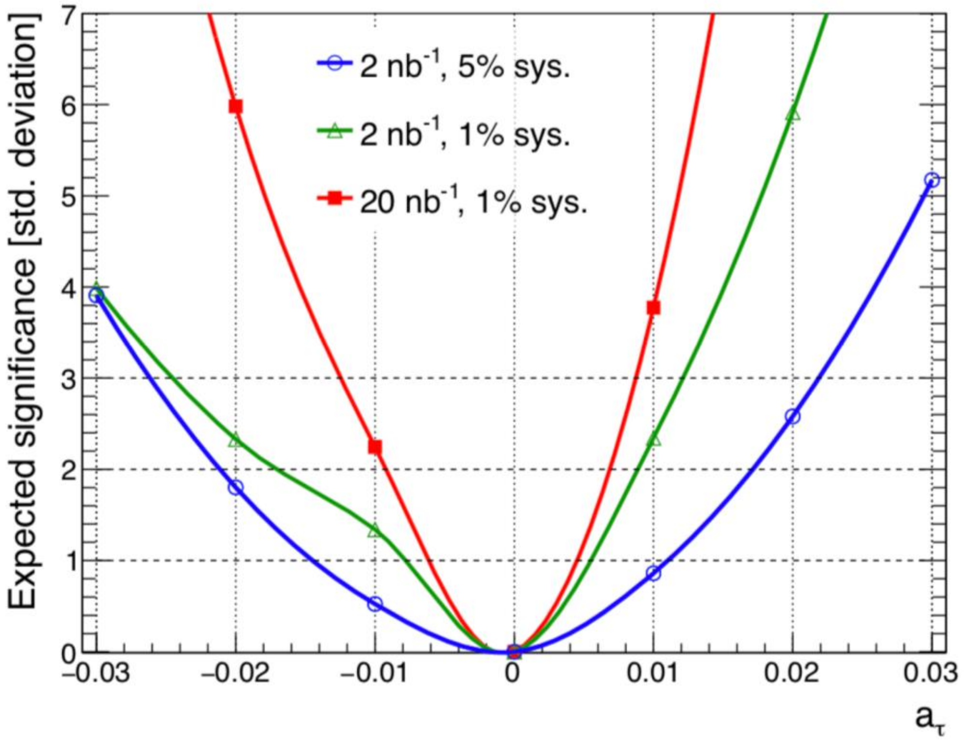
poorly constrained due to short lifetime

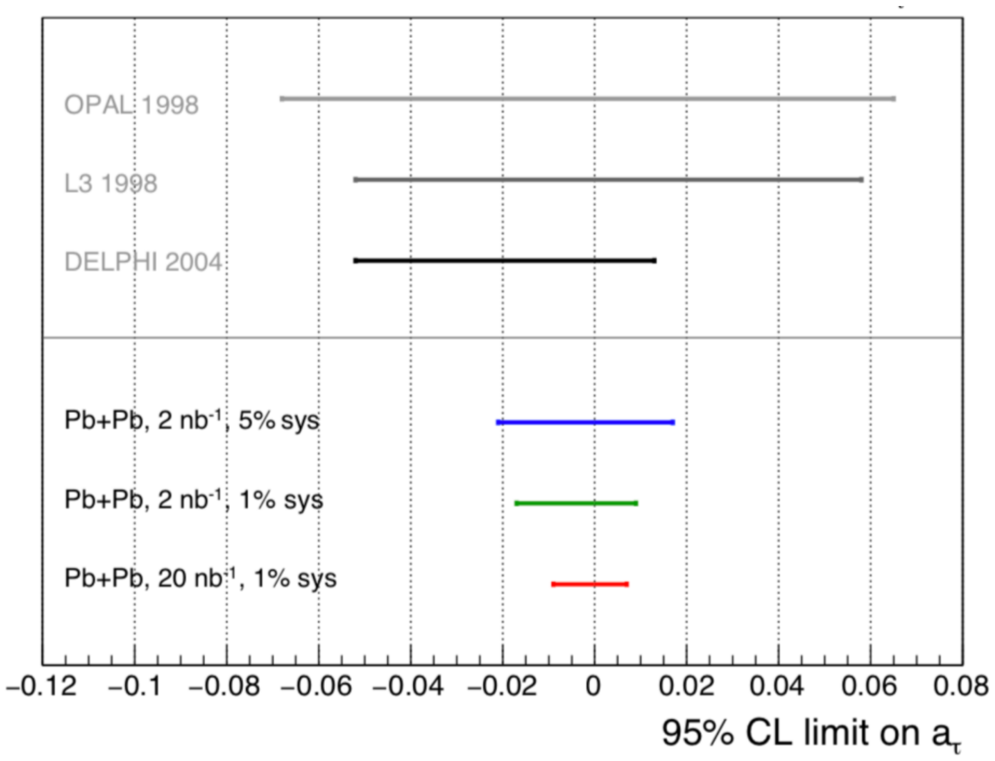
Jan Hajer

Measure in HI



- Rely on the large EM field in heavy ion collisions to produce tau leptons.
- Significant improvement on a_τ expected with 2-20 nb^{-1} of PbPb





HI and NP: Sexaquark

$S = uuddss$

spin, colour, and flavour singlet

$$m_S \approx 2m_p \qquad B = -2$$
$$Q = 0 \qquad S = -2$$

no pion interactions

Tightly bound and compact

$r_S \approx 0.2\,\mathrm{fm}$

Dark matter candidate

Quasi stable with $\Omega_{\mathrm{DM}}/\Omega_b \approx 5$ without free parameters

So far not excluded

Despite searches for the H-dibaryon with same quark content

Because search relies on

- unstable particle
- heavy particle ($> 2\,\mathrm{GeV}$)
- interaction with Λ

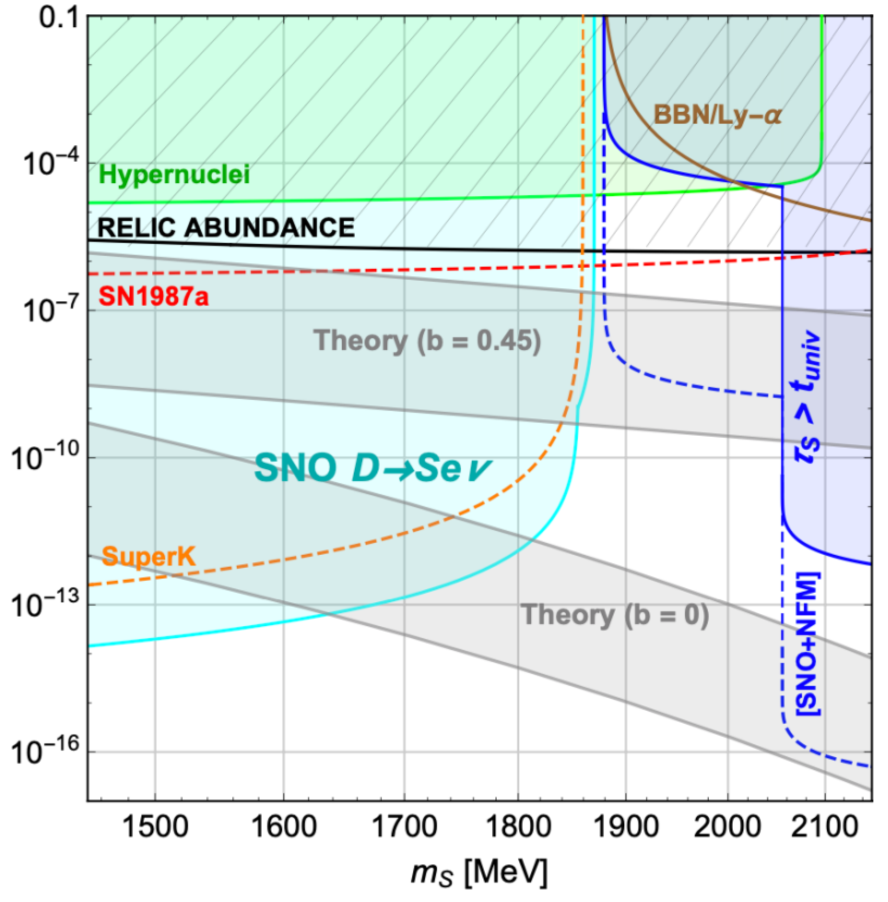
However

S is similar to neutron

$$\{\pi : n : S\} \approx \{1 : 0.01 : 10^{-4}\}$$

Exclusion bounds on $S \to \Lambda\Lambda$

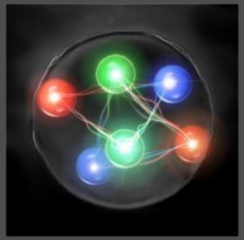
effective Yukawa coupling



Proposal

search in HI collisions behind a neutron absorber shield

- Sexaquark-to-baryon density ratio can be predicted by simple statistical arguments in the QGP-hadronization transition with known QCD parameters (quark masses and T_{QCD}) to be ≈ 4.5 ± 1
- **Reply on heavy ion collision to produce sexaquarks**



Jan Hajer

OppOrtunities at the LHC

Jasmine Therese Brewer, Aleksas Mazeliauskas, Wilke van der Schee

1. Workshop was a success
   - On average 186 unique participants per day over 5 days
   - Many new computations and projections

2. One crucial discussion point: the colliding energy
   - Maximum magnetic field: around 7 TeV
   - But perhaps no *pp* reference available? It is however difficult to lower the energy

June CERN council:
Potential OO pilot run → Special run
Full LHC exploitation

Full LHC exploitation : Oxygen run and SND

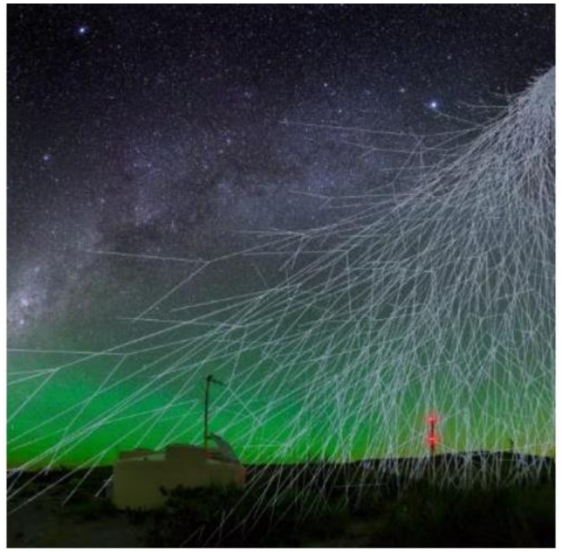
Special **O-O and p-O run**
- Physics motivations: study of emergence of collective effects in small systems; measurements relevant for cosmic rays (extensive air shower modelling), etc.
- Experiments requested ~ nb^{-1} for each of OO and pO. ~ 1 week (including commissioning), most likely in 2024
- No impediment from accelerators but radiological impact of high-intensity oxygen beam requires mitigation measures and additional beams stoppers to be able to access Booster when LEIR operates.
- Needed resources allocated in this MTP

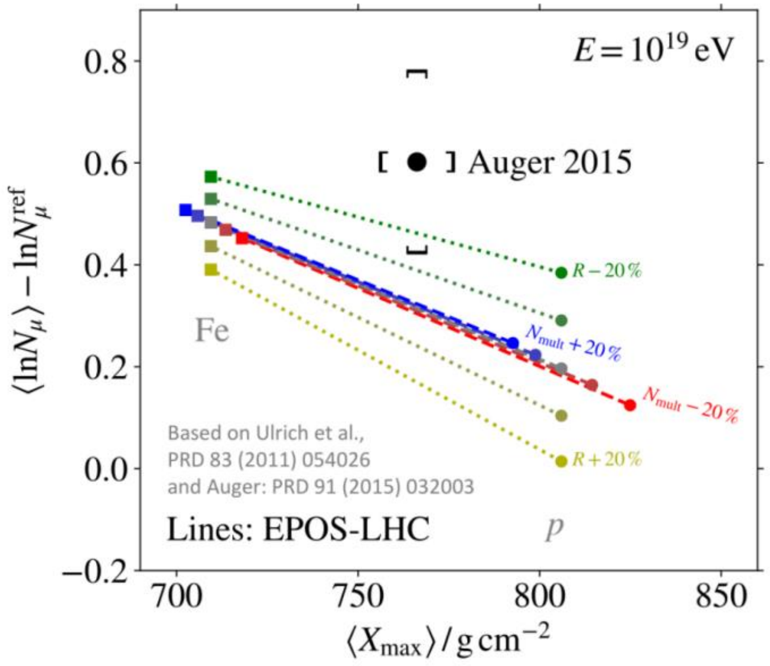
Wilke van der Schee

pO & OO: Muon Puzzle in Cosmic Air Shower

Muon puzzle in cosmic air showers

- Cascade of energetic collisions, producing muons and photons
- Difficult to *simultaneously* predict
  - Number of muons
  - Depth of air shower (in air density units)





Wilke van der Schee

- **Direction** from particle arrival times
- **Energy** from size of **fluorescence light**
- **Mass** from **depth of shower maximum** and size of **μ component**

$$E_{\mathrm{cal}} = \int_0^\infty \left(\frac{dE}{dX}\right)_{\mathrm{ionization}} dX$$

X_{max} Shower depth and Mass
Difference Fe to p: 100 g cm-2 deeper

N_μ Number of muons and Mass
Difference Fe to p: 40 % more muons

Experimental accuracies

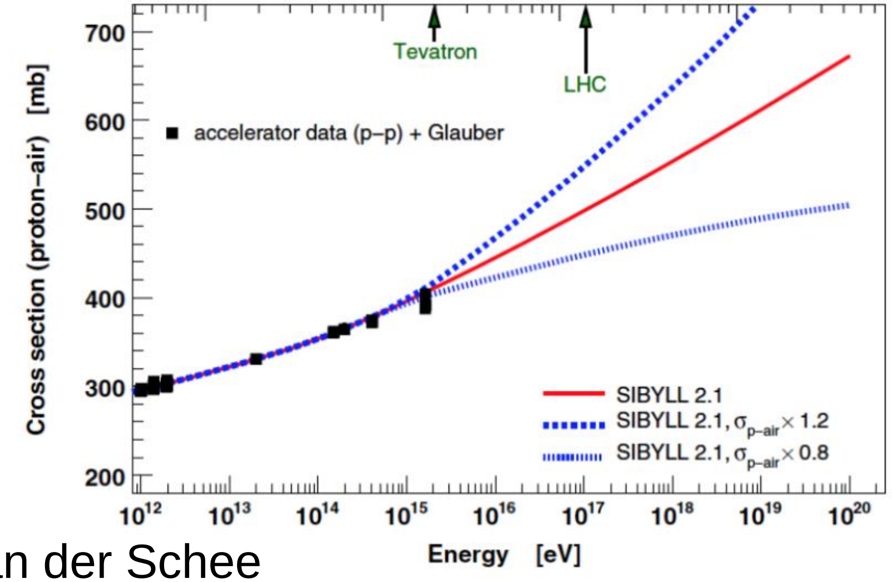
Direction	$0.5 - 1.5^\circ_{stat}$	
Energy	$10 - 20\ \%_{stat}$	**$14\ \%_{sys}$**
X_{max}	$15 - 25\ \mathrm{gcm^{-2}}_{stat}$	**$10\ \%_{sys}$ of Δ(p,Fe)**
N_μ	$20\ \%_{stat}$	**$25\ \%_{sys}$ of Δ(p,Fe)**

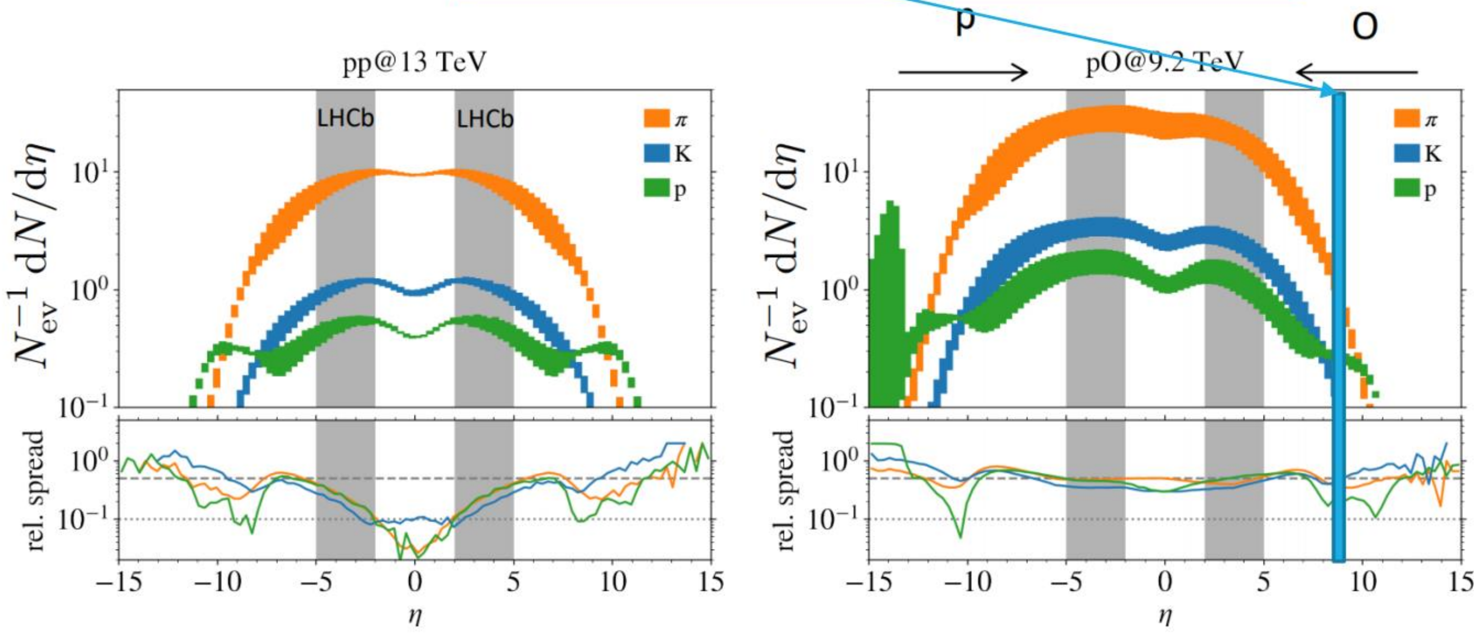
pO & OO: Muon Puzzle in Cosmic Air Shower

Muon puzzle in cosmic air showers

- Cascade of energetic collisions, producing muons and photons
- Difficult to *simultaneously* predict
  - Number of muons
  - Depth of air shower (in air density units)

LHCf: this is were most of the energy is deposited (ends after run 3)

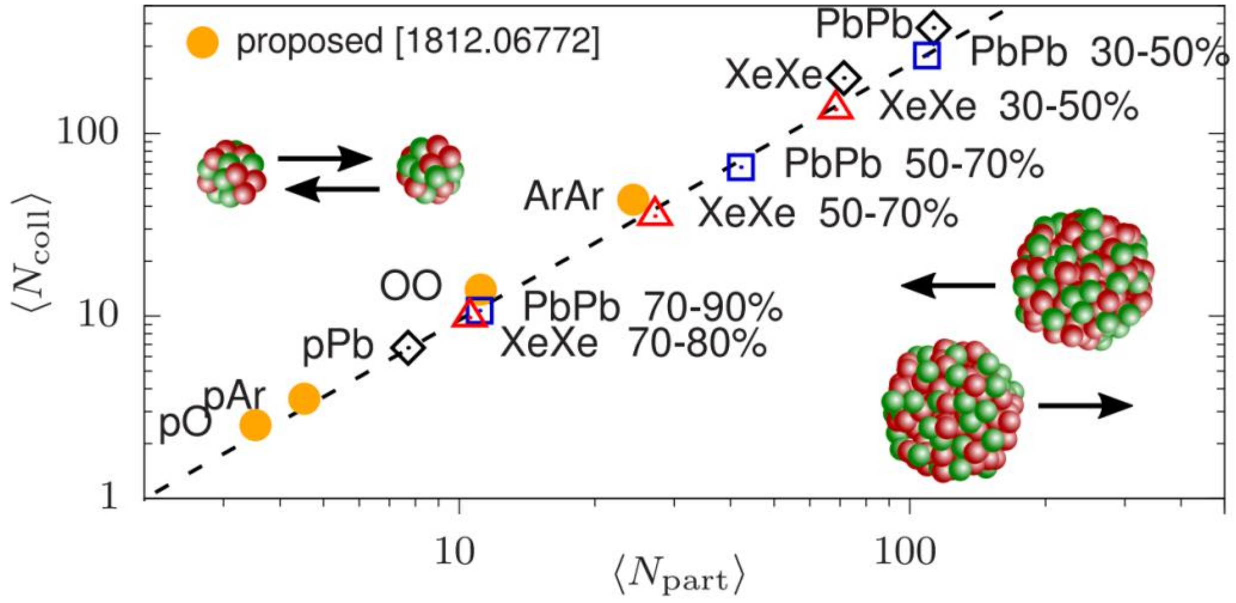


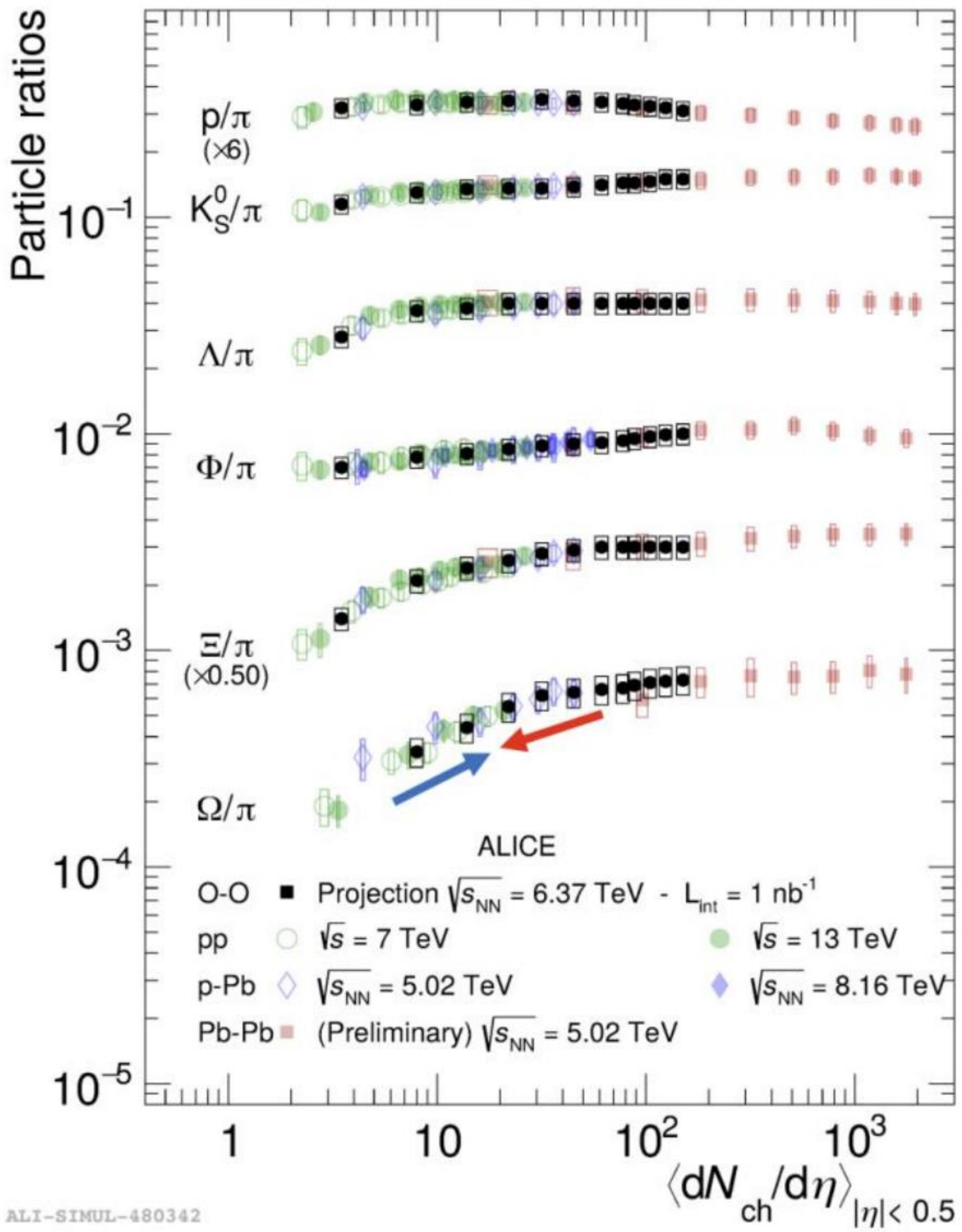


Wilke van der Schee

pO & OO: From pQCD to Thermal

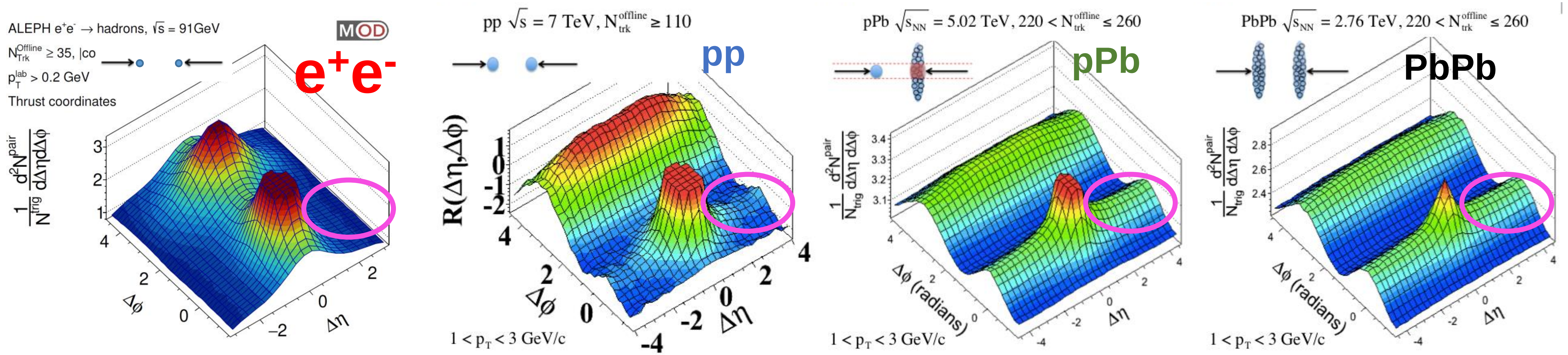
- Strangeness enhancement from ALICE particle ratios measurement
- Effect increases with multiplicity, not described by PYTHIA. Not yet fully understood.
- OO: provide unique opportunity to smoothly connect pPb and PbPb



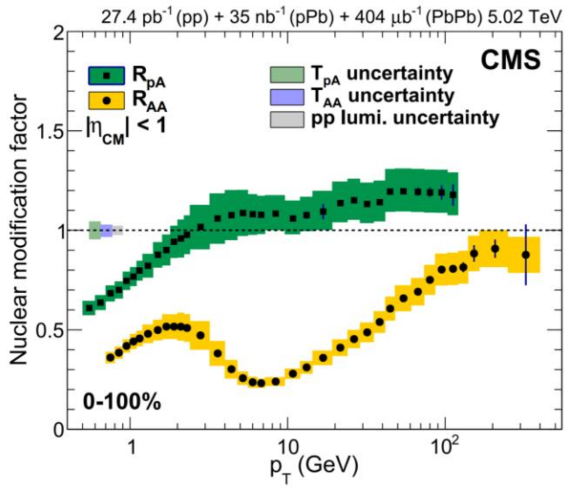


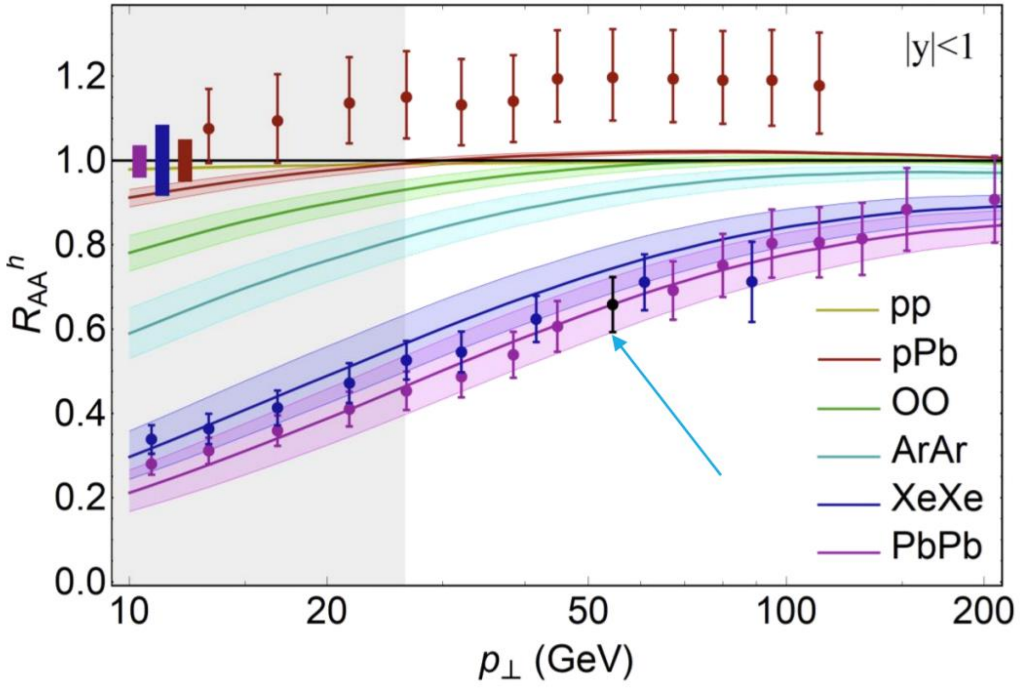
Wilke van der Schee

pO and OO: Jet Quenching in Small System?



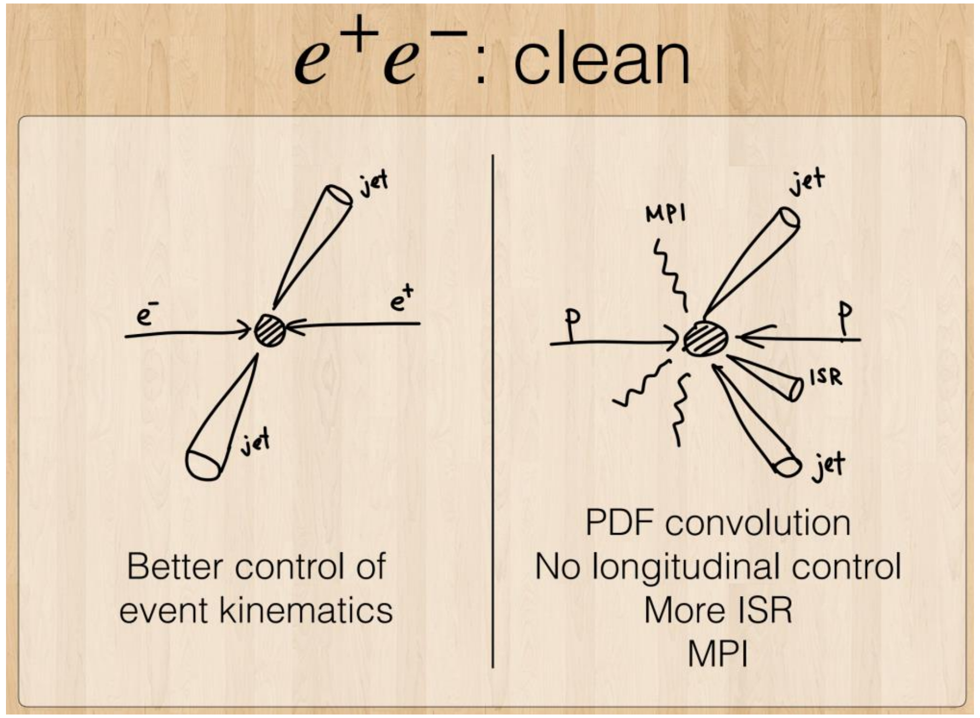
1. There seems to be flow
   - Quite some modeling, but everything consistent with hydro (does not prove hydro!)
2. But: nuclear modification > 1: **no (naive) jet/hadron energy loss**





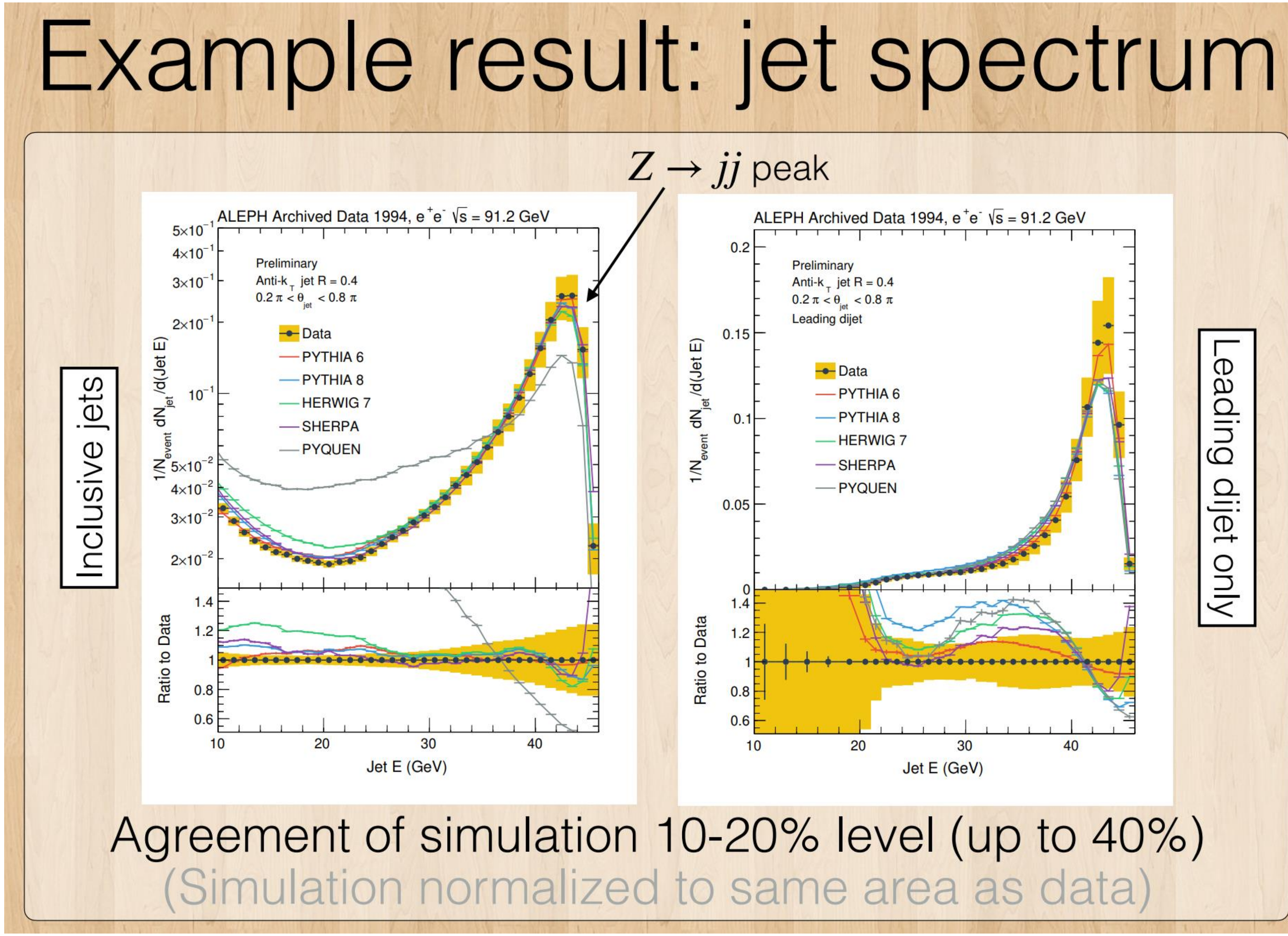
Wilke van der Schee

"Anti-k_T" Jet in e^+e^- collisions



Since the end of LEP operation, significant progress has been made in jet definition and jet algorithms:

- Jet substructure observables have been widely explored in pp and HI collisions
- Novel tools for jet flavor identification, EW boson & top tagging and studies of QGP
- However, those techniques are not yet used in $e^+ e^-$ annihilation data

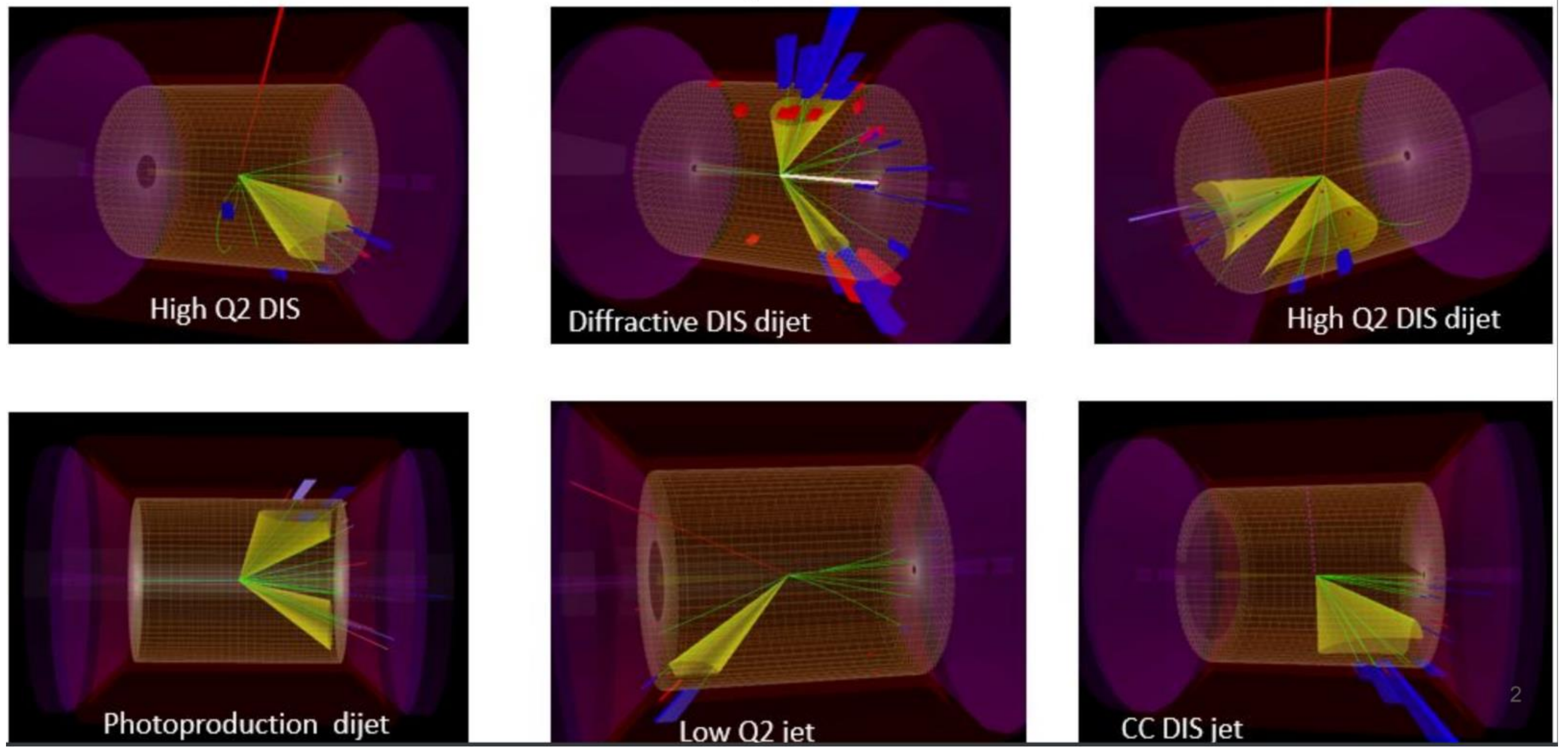


Yi Chen

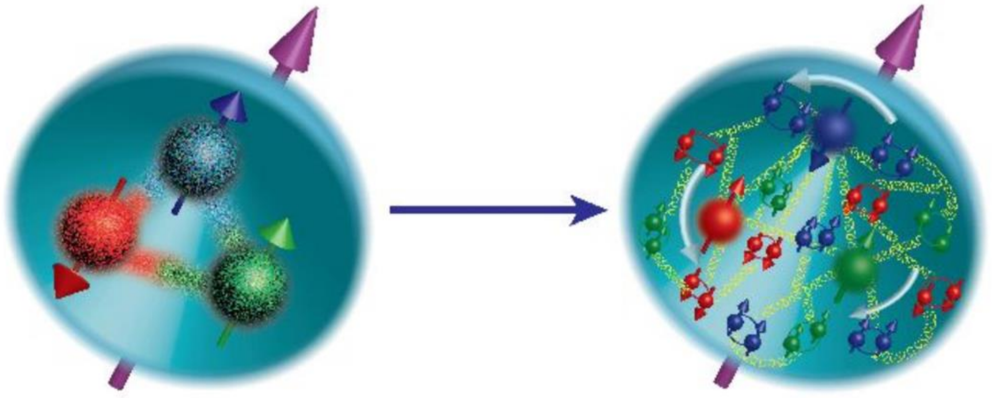
https://arxiv.org/abs/2108.04877

Jet @ EIC

The EIC, a jet factory, will make the first jets in nuclear DIS and proton-polarized DIS



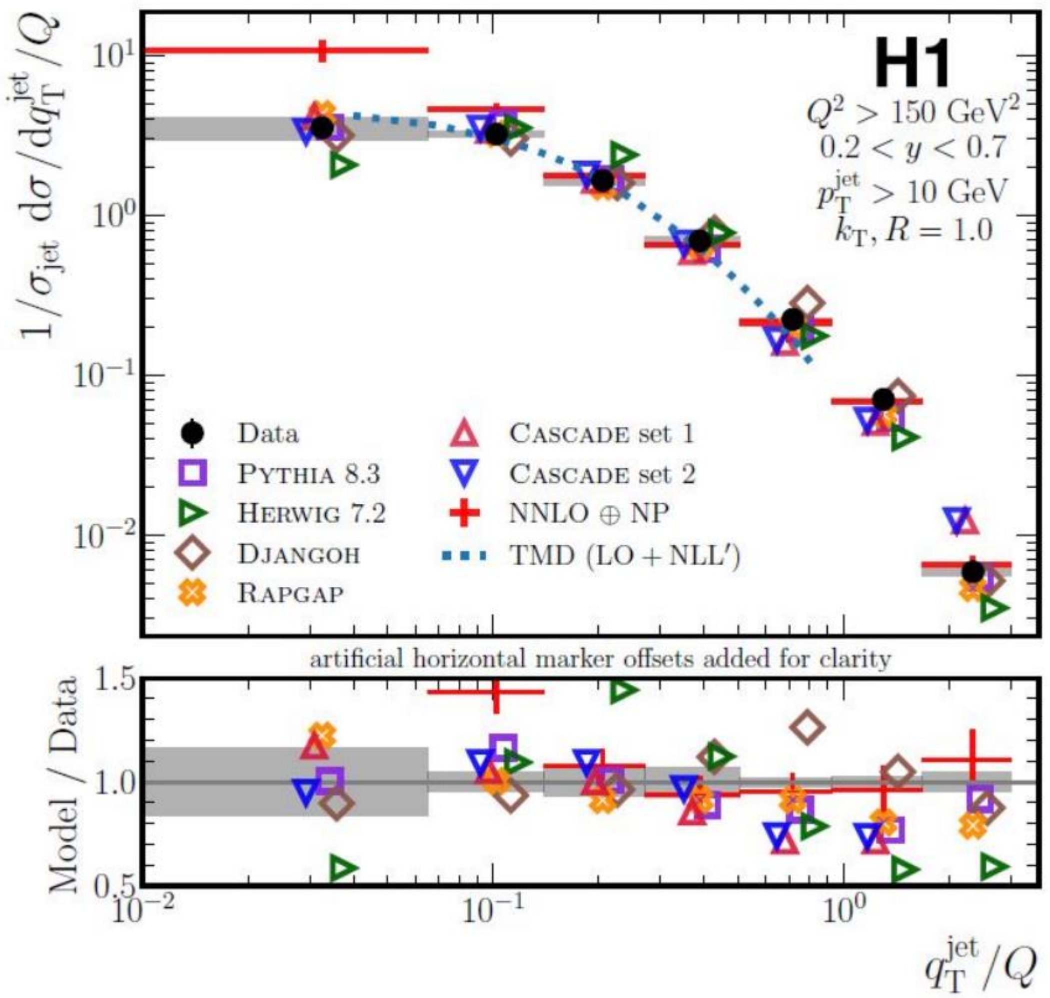
We will probe unexplored aspects of the theory of strong interactions that govern the "evolution" of the 3D structure with energy

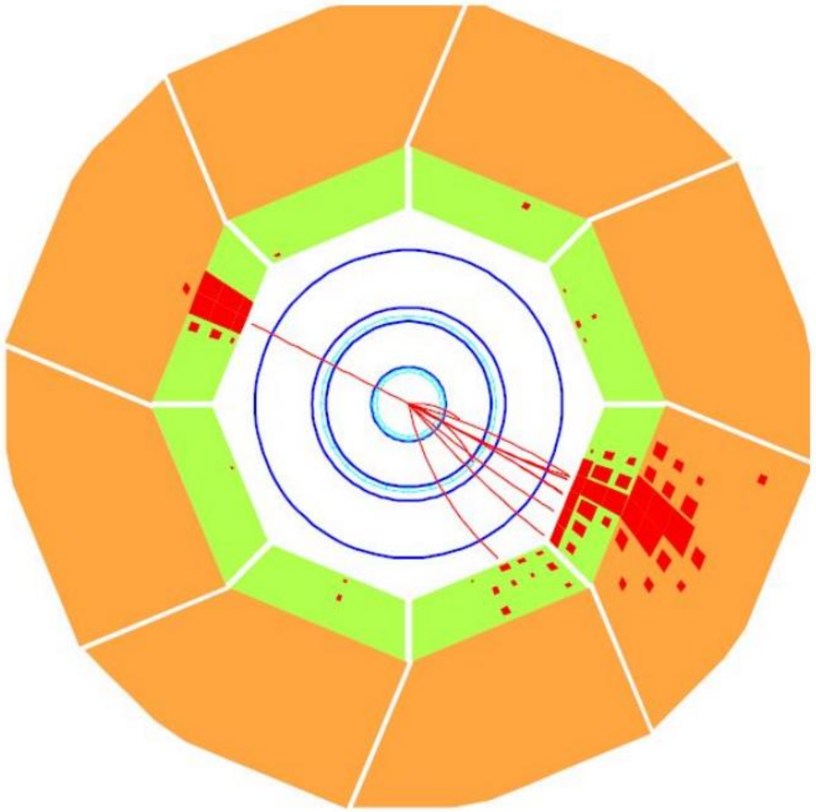


Miguel Arratia

Example: New H1 measurement

New H1 measurement https://arxiv.org/abs/2108.12376

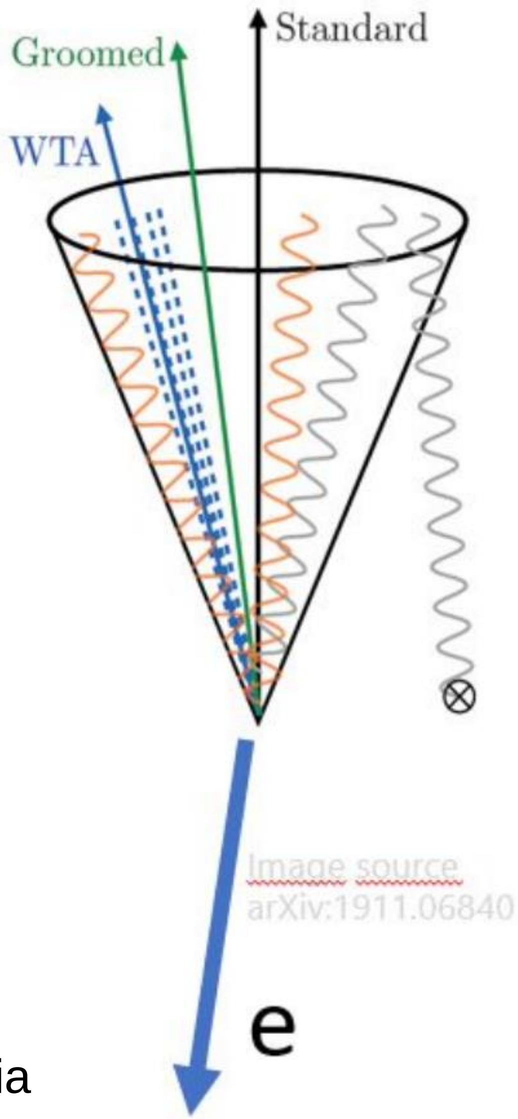




Miguel Arratia

Development of Jet Substructure Observables

Jet substructure, the key to novel TMD studies



Recent example:
"T-odd jets" (arXiv:2104.03328)

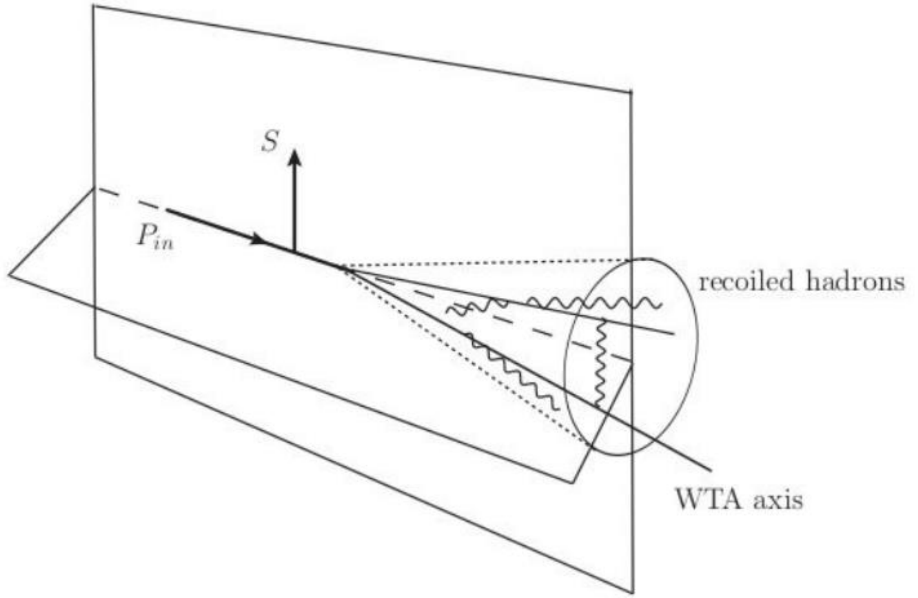
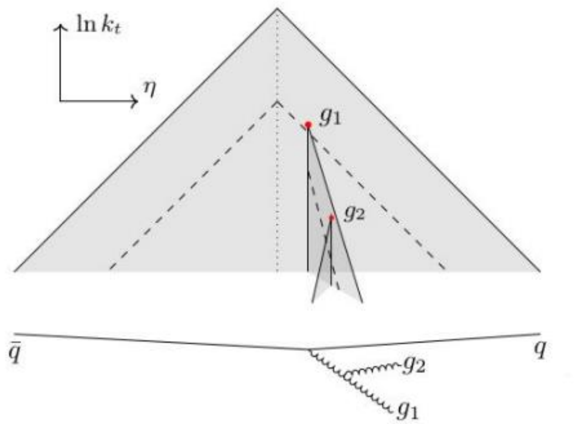


FIG. 1. Origin of the jet T-odd contributions. The WTA jet axis lies outside the plane by the spin S and P_{in}, to allow for the asymmetry due to the quantum correlation between parton's spin and its hadronization about the plane.

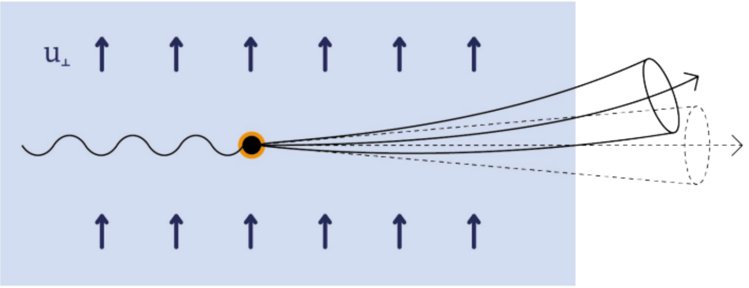
- **Grooming**
  Gutierrez et al. JHEP 08 (2019) 161 . Makris et al. JHEP 07 (2018) 167
- **Jet axes**
  Cal et al. JHEP 04 (2020) 211,
  Niell et al. JHEP04 (2017)020
  Liu et al. arXiv: 2104.03328
- **Declustering?**
  arXiv:2103.16526



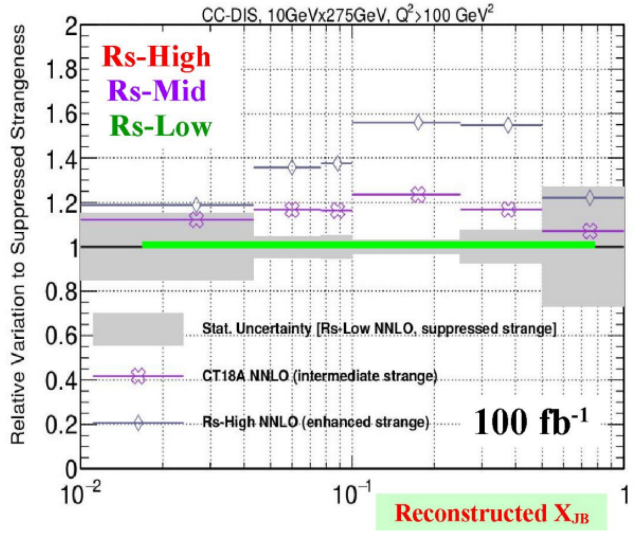
Miguel Arratia

Heavy Flavor Physics @ EIC

A. Sadofyev, F. Olness, S. Moch, P. Wong, D. Shao, X. Li, Y. Makris, Y. Zhao, Z. Liu



- Density effects on parton propagation in e+A collisions and hadronization

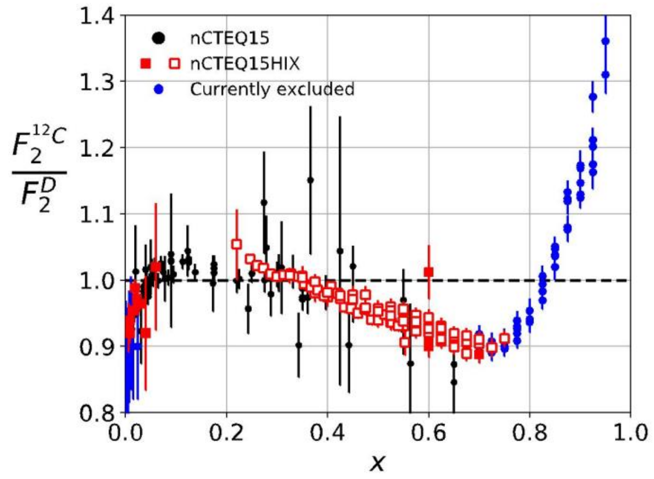


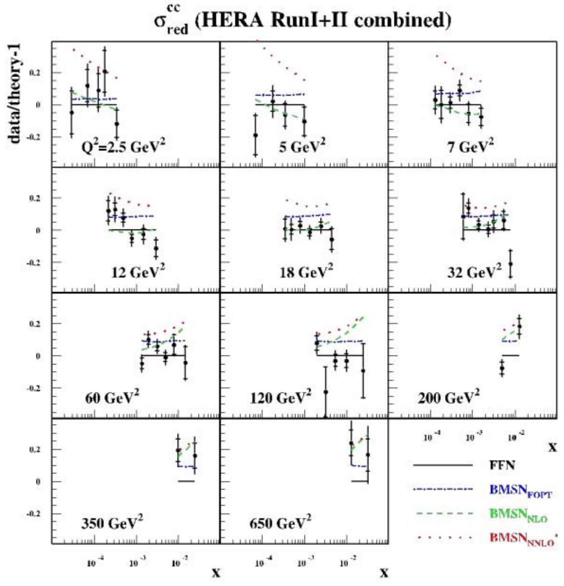
- Charm jets as probes of strangeness at the EIC

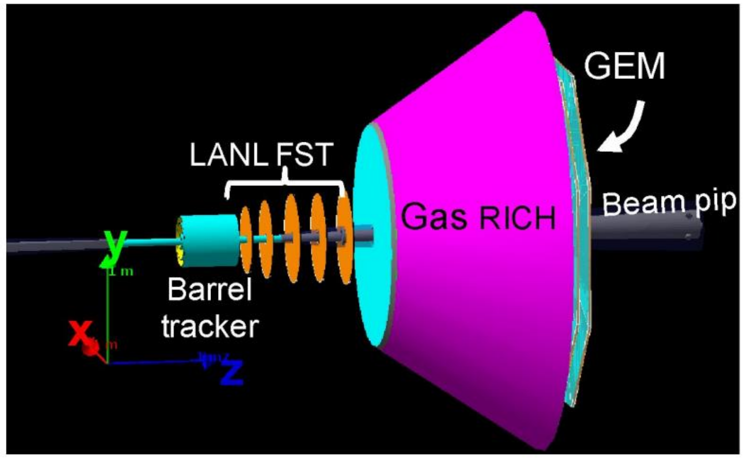
Stephen Sekula

Heavy Flavor Physics Goal and EIC Detector

- Deciphering QCD – nuclear PDFs and nCTEQ
- The Heavy Flavor Schemes at EIC
- A Forward Silicon Tracker for the Future Electron-ion Collider Experiments







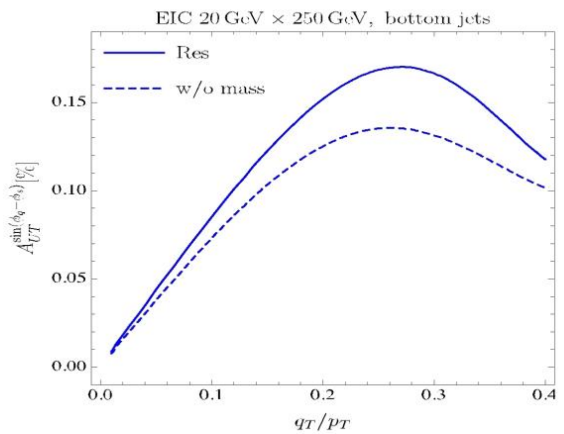
Stephen Sekula

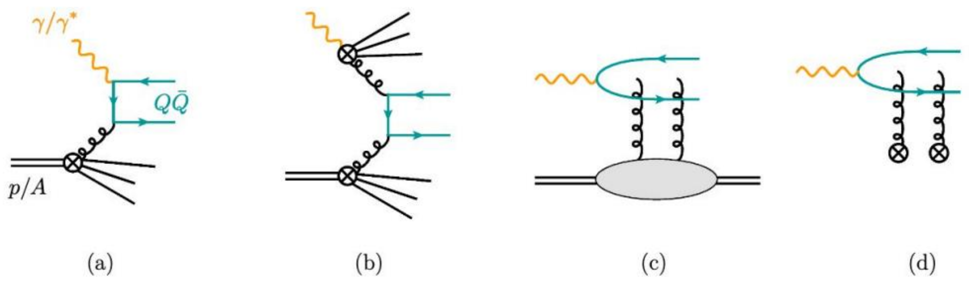
Heavy Favor Observables @ EIC

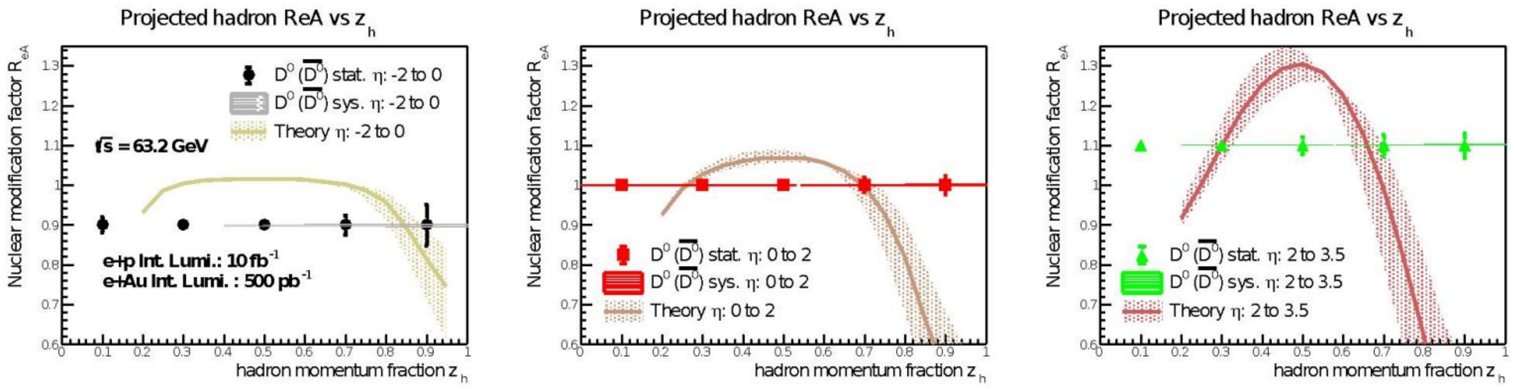
- Heavy Flavor dijets and the Sivers asymmetry

- Quarkonium production mechanisms at the EIC

- Measurements of heavy flavor mesons and hadronization



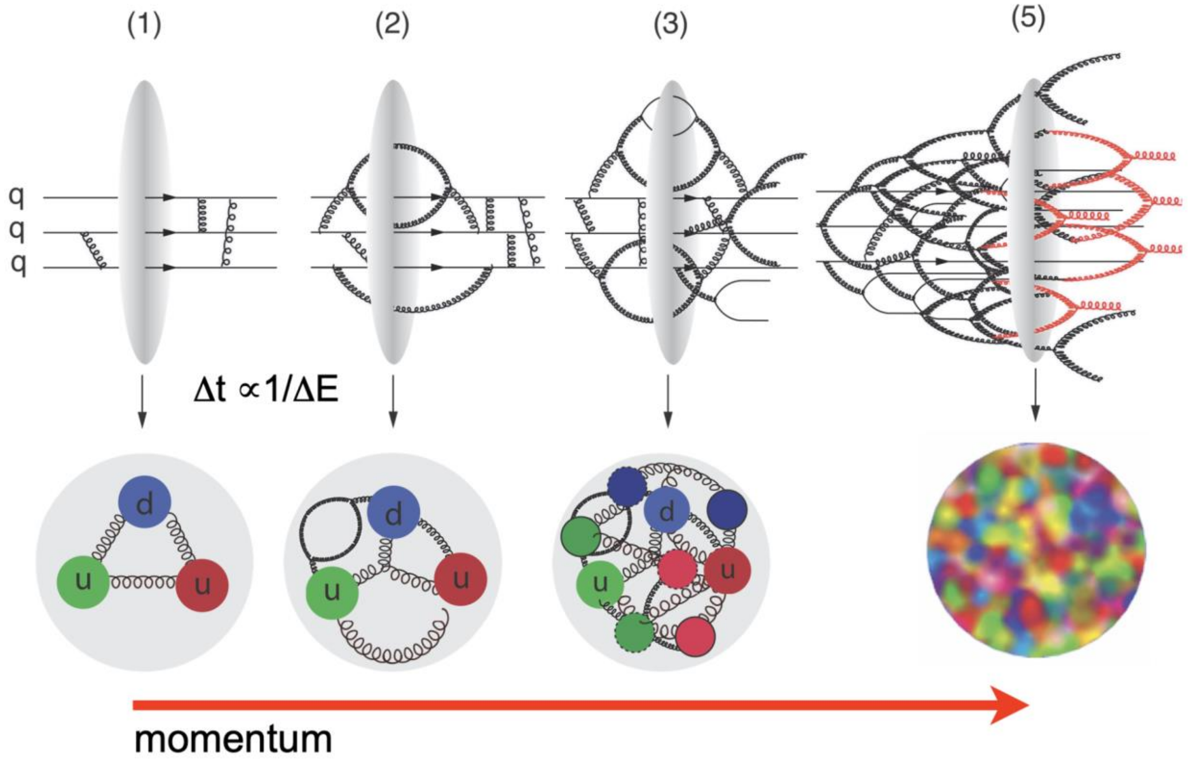




Stephen Sekula

Gluon Saturation @ EIC

The boosted proton



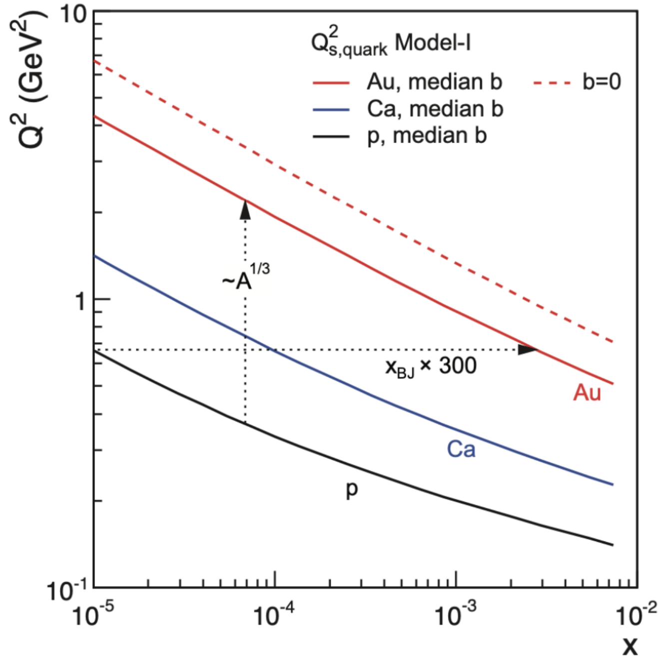
for the most recent review: A. Morreale, F. Salazar, Universe 7 (2021) 8, 312 • e-Print: 2108.08254

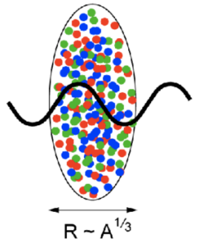
Bjoern Schenke

Observables

- Inclusive: Structure functions
- Semi-inclusive: dihadron, dijet correlations
- Diffractive processes: e.g. ratio of diffractive and total cross-section, vector meson production, …

Using heavier ions helps with accessing the saturated regime



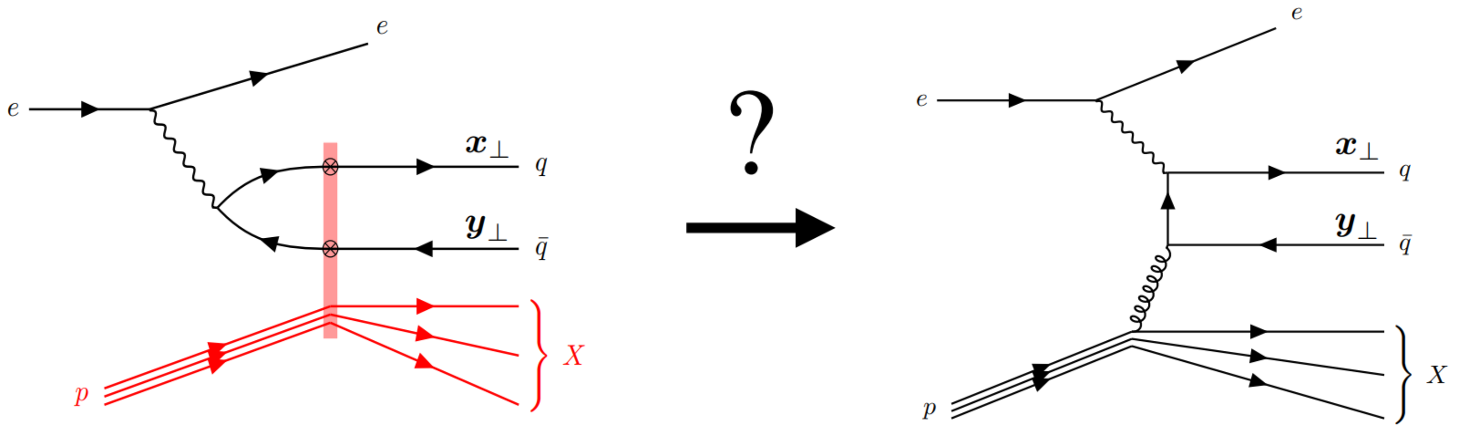


$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

Reveal The Genuine Saturation Effect

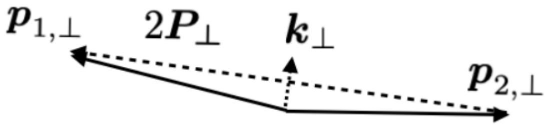
Matching TMD and CGC frameworks at small-x

CGC, improved TMD, and TMD frameworks



Mäntysaari, Mueller, Salazar, Schenke. 1912.05586
Boussarie, Mäntysaari, Salazar, Schenke. 2106.11301

$$\mathrm{d}\sigma_{\mathrm{CGC}} = \underbrace{\mathrm{d}\sigma_{\mathrm{TMD}} + \overbrace{\mathcal{O}\left(\frac{k_\perp}{Q_\perp}\right)}^{\text{kinematic}}}_{\mathrm{d}\sigma_{\mathrm{ITMD}}} + \overbrace{\mathcal{O}\left(\frac{Q_s}{Q_\perp}\right)}^{\text{genuine}}$$



$$Q_\perp \sim P_\perp, Q$$

TMD valid $k_\perp, Q_s \ll Q_\perp$

back-to-back hadrons/jets
and transverse momenta larger than sat scale

see also: Dominguez, Marquet, Xiao, Yuan. 1101.0715, Altinoluk, Boussarie. 1902.07930, Boussarie, Mehtar-Tani. 2001.06449

Improved TMD valid $Q_s \ll Q_\perp$

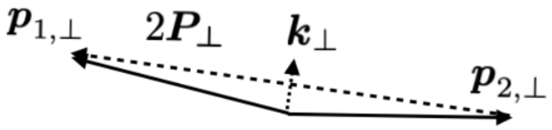
transverse momenta larger than saturation scale

No need for back-to-back!

Bjoern Schenke

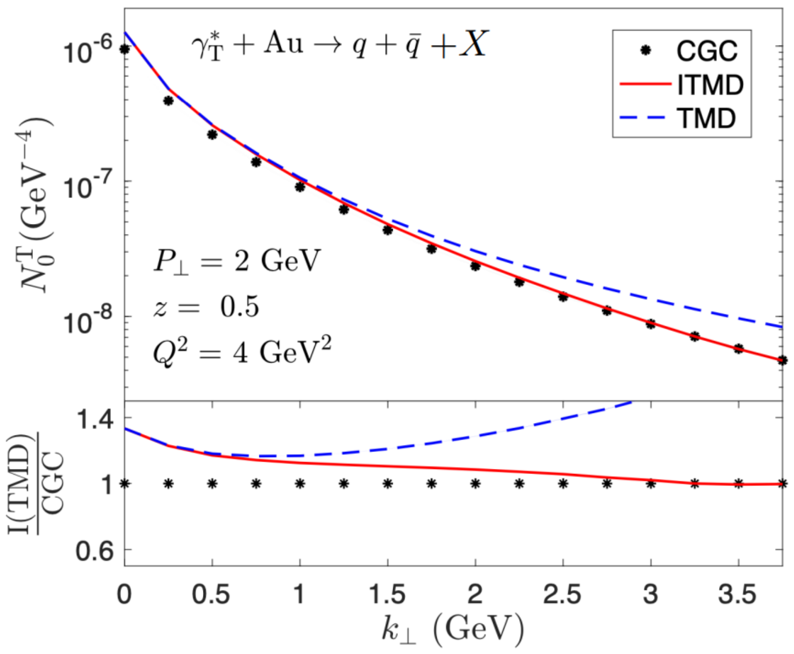
Matching TMD and CGC frameworks at small-x

Kinematic and genuine saturation effects at the EIC

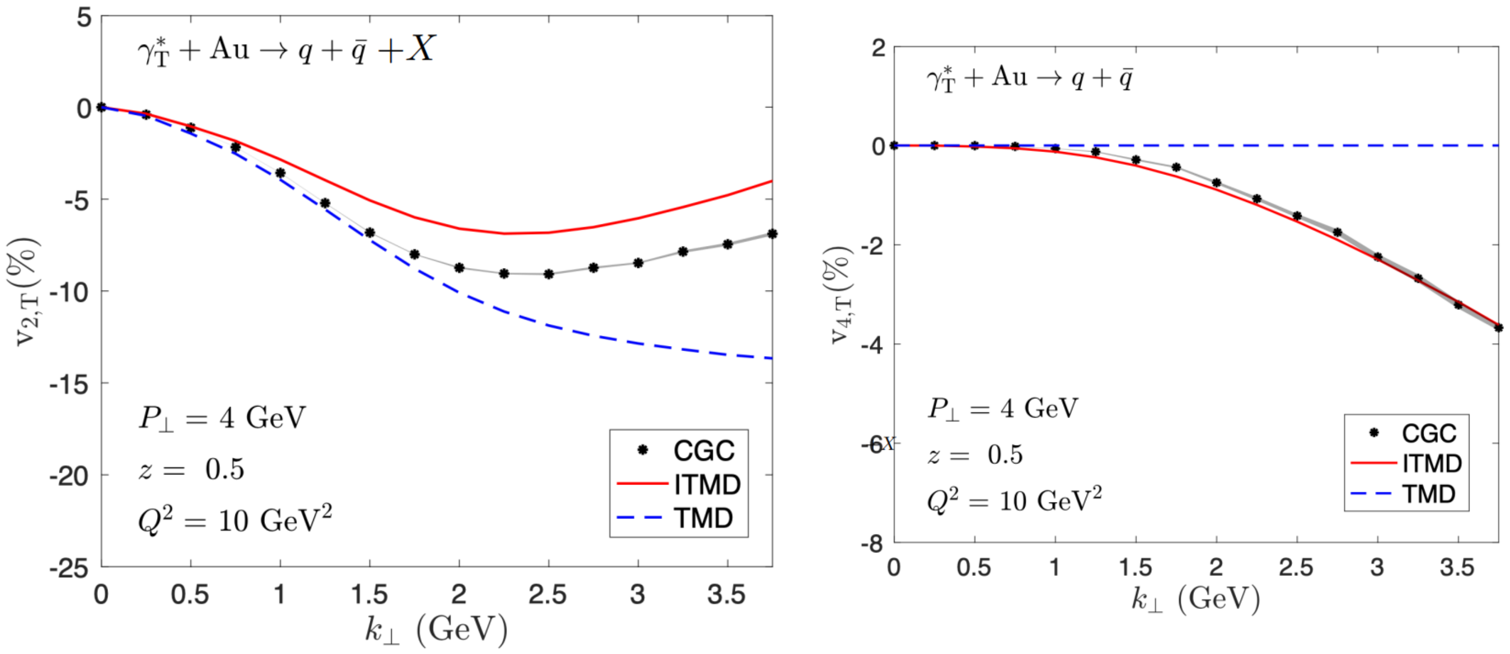


Boussarie, Mäntysaari, Salazar, Schenke. 2106.11301

Differential yield



Momentum imbalance azimuthal anisotropies



CGC shows further suppression relative to (I)TMD in back-to-back limit

Anisotropies modified in ITMD and CGC

Bjoern Schenke

Summary and Plan

- **New Physics in HIC:**
  - ALP searches, monopole, tau g-2 and sexaquark
  - Preparation for the Snowmass document
- **Physics with pO and OO collisions:**
  - Important data for cosmic ray physics
  - Reveal jet quenching effect in small collision systems
- **Jets in e^+e^-: reference to pp, EIC and HI data**
- **EIC Physics:**
  - Yellow report has become public
  - New developments in the EIC detector design for jet and heavy flavor physics
  - New developments on jet related observables
  - Advance in revealing the genuine saturation effects and NLO computation on the gluon saturation observables
  - Convert the collected inputs to Snowmass documents
- NP LRP timeline: to be decided by the end of the 2021

- Backup slides

EIC

- EIC topic coordinators:
  - Heavy Flavor @ EIC: Xin Dong (LBL), Stephen Sekula (SMU), Ivan Vitev(LANL)
  - Proton tomograph @ EIC for HEP applications: Timothy Hobbs (SMU), Salvatore Fazio (BNL), Alexey Prokudin (PSU), Alessandro Vicini (Milan)
  - Gluon saturation @ EIC: Tuomas Lappi (Jyvaskyla), Soeren Schlichting (Bielefeld), Renaud Boussarie (BNL), Bjoern Schenke (BNL)
  - EW&BSM @ EIC: Yulia Furletova (JLAB), Ciprian Gal (SBU), Claire Gwenlan (Oxford)
  - Jets @ EIC: Miguel Arratia (UCR), Zhong-Bo Kang (UCLA), Stefan Prestel (Lund)

HIC

- HIC topic coordinators assigned
  - Search for New Physics with Heavy Ion Beam: Marco Drewes (Theory) and Andrea Giammanco (CMS).
  - Quarkonia and exotic hadron production in relativistic heavy ion collisions: Matthew Durham (LHCb) and Xiaojun Yao (Theory)
  - Ultra Peripheral Heavy Ion Collisions: Zhangbu Xu (STAR), Jian Zhou (Theory), Mariusz Przybycien (ATLAS/ZEUS)
  - High Density QCD in Small Collision Systems: Jaki Noronhahostler (Theory), Wei Li (CMS/STAR), Dennis Perepelitsa (ATLAS/sPHENIX)
  - Heavy Flavor Production in Heavy Ion Collisions: Gian Michelle Innocenti (ALICE), Jing Wang (CMS), Jin Huang (sPHENIX)
  - Jet and Jet Substructure in Heavy Ion Collisions: James Mulligan (ALICE), Leticia Cunqueiro Mendez (ALICE), Yi Chen (CMS), Anne Sickles (ATLAS)
  - EW Physics in Heavy Ion Collisions and the Impact to nuclear PDF: Hannu Paukkunen (Theory), Georgios Krintiras (CMS) and Emilien Champon (CMS)

Magnetic Monopole

Magnetic monopoles

Magnetic field in 5.02 TeV PbPb

$$|B| \simeq 4 \cdot 10^{16}\,\mathrm{T} \simeq 7\,\mathrm{GeV}^2$$

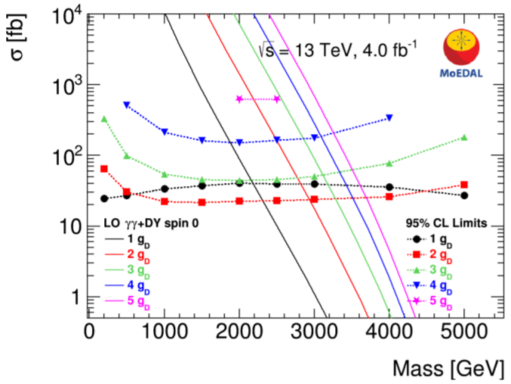
Magnetic charges

$$\nabla \cdot E = \rho_E \;,\; \nabla \times E = -\partial_t B - j_M$$
$$\nabla \cdot B = \rho_M \;,\; \nabla \times B = -\partial_t E - j_E$$

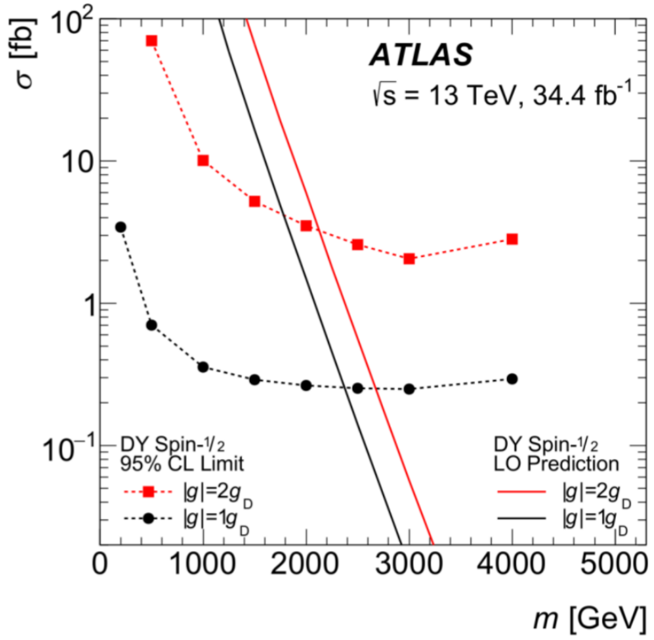
Dirac quantisation

$g \in g_D\mathbb{Z}$ with $g_D = 2\pi / e_0$

MoEDAL 2019



ATLAS 2019



Drell-Yan crosssection is wrong

$e \to g = 2\pi / e$ Duality

Because $g_D \approx 20.7 \gg 1$

Process is non-perturbative

Instanton tunneling action

$$\Gamma \propto e^{-S_{\mathrm{inst}}}$$

Monopole Schwinger production

$$\Gamma = \frac{g^2|B|^2}{8\pi^3} \exp\left(\frac{g^2}{4} - \frac{\pi m^2}{g|B|}\right)$$

Needs strong magnetic field

Time dependence

enhanced production for rapid pulses

Spatial inhomogeneity

Effect not known

Solitonic monopole size

Enhances production

Jan Hajer